Comment on '*Evidence for pairing above T_c from the dispersion in the pseudogap phase of cuprates*' by A. Kanigel et al

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In a recent preprint [cond-mat/0803.3052] A. Kanigel *et al* report evidence for Bogoliubov-type excitations in the pseudogap phase in the anti-nodal region, where a robust pseudogap remains well above T_c. This important experimental result has been theoretically predicted by us almost 6 years ago on a basis of the phenomenological boson fermion model. An earlier theoretical prediction on the basis of this model was that of a pseudogap in the electron DOS, setting in at some temperature T^* and evolving into the superconducting gap upon approaching T_c. A natural logical pursuit of this early work was to show that, in order to have a superconducting state evolved out of a pseudogap state, the diamagnetic bosonic pair fluctuations (characterizing the pseudogap phase) have to be propagating modes and should be phase correlated over some finite distances above T_c. If so, then the pseudogap feature has to be reflected in characteristic features of the single particle excitations, showing remnants of the Bogoliubov modes inherent in the superconducting phase. Such Bogoliubov modes result from the dynamical feedback effects between single electron excitations and dynamical local pairing fluctuations. We briefly recollect here our theoretical results and confront them with the recent experimental findings.

The mechanism of high temperature superconductivity (HTSC) is widely believed to be related to the strong correlations between electrons in the 2-dimensional CuO_2 planes. However, no specific microscopic model has been so far fully accepted, mainly because of conflicting interpretations of the pseudogap state in the underdoped cuprates. The recent experimental data [1] unambiguously confirm that the pseudogap is a signature of pairing fluctuations. For the regions in the Brillouin zone, where the pseudo gap is present above T_c, these authors have indeed detected such a Bogoliubov-type excitation spectrum, as predicted by us theoretically [2].

There are many theoretical approaches proposed to explain HTSC materials [3]. Many of them rely on assumption that d-wave superconductivity originates from the non-retarded intersite pairing. The corresponding two-body interactions are then transformed away via the usual Hubbard Stratonovich transformation, which introduces auxiliary bosonic pairing fields. Generally, many studies focus on the saddle point (mean-field) solution plus small (Gaussian) corrections around it. Such procedure is however questionable in the HTSC cuprates, where the fermion and boson degrees of freedom are strongly mixed with one another.

We have for that reason preferred to follow a phenomenological approach assuming that along the antinodal directions the underlying physics can be described in terms of itinerant fermions hybridized with the local pairs via Andreev-type scattering. This, so-called Boson Fermion model was proposed well before the discovery of HTSC [4]. Already on a meanfield basis, this model showed the intricate interplay between pairing correlations and the opening of a gap in the single particle DOS.

Upon going beyond the mean field, it clearly indicated a persisting pseudogap above T_c [5]. This theoretical prediction was verified experimentally a year later or so by the Argonne and Stanford groups.

Following this initial theoretical work, it became clear that in order to proceed from the pseudogap into the superconducting phase upon lowering the temperature, one required a selfconsistent approach, treating the pair fluctuations and the single particle excitations on the same footing. For that to achieve we have used a numerical RG approach [6], which allowed us to account for a mutual renormalization of the single and paired electrons via coupled flow equations [7]. From their solution we derived the resulting single particle spectral function $A(\mathbf{k},\omega)$ [2]. For the energies $\omega<0$ (which are probed by the direct photoemission), this spectral function for $T \le T_c$ turned out to have the following form [7]

$$A(\mathbf{k},\omega<0) \; = \; |u_{\mathbf{k}}|^2 \delta\left(\omega - \tilde{\xi}_{\mathbf{k}}\right) + |v_{\mathbf{k}}|^2 \frac{\Gamma_{\mathbf{k}}/\pi}{(\omega+\tilde{\xi}_{\mathbf{k}})^2+\Gamma_{\mathbf{k}}^2} + A_{bg}(\mathbf{k},\omega) \tag{1}$$

with qusiparticle dispersion $\tilde{\xi}_{\mathbf{k}} = \sqrt{(\varepsilon_k-\mu)^2+\Delta^2_{\mathbf{k},pg}}$. $\Gamma_{\mathbf{k}}$ denotes a broadening which increases with increasing temperature, while the pseudogap $\Delta_{\mathbf{k},pg}$ hardly changes, provided we are well below below T^* ($T_c \le T << T^*$). The remaining background $A_{bg}(\mathbf{k},\omega)$ is rather rigid and its contribution is not relevant to particle-hole mixing arising from the pairing fluctuations. Obviously for the positive energies (measured by the inverse photoemission) the spectral function becomes $A(\mathbf{k},\omega>0) = |v_{\mathbf{k}}|^2\delta(\omega+\tilde{\xi}_{\mathbf{k}}) + |u_{\mathbf{k}}|^2 \frac{\Gamma_{\mathbf{k}}/\pi}{(\omega-\tilde{\xi}_{\mathbf{k}})^2+\Gamma^2_{\mathbf{k}}} + A_{bg}(\mathbf{k},\omega)$.

In figure 1 we reproduce [2] the corresponding results obtained for the spectral function near the antinodal region within the boson-fermion model scenario. One clearly notices the emergence of the Bogoliubov-type spectrum both, below and above T_c. In the pseudogap

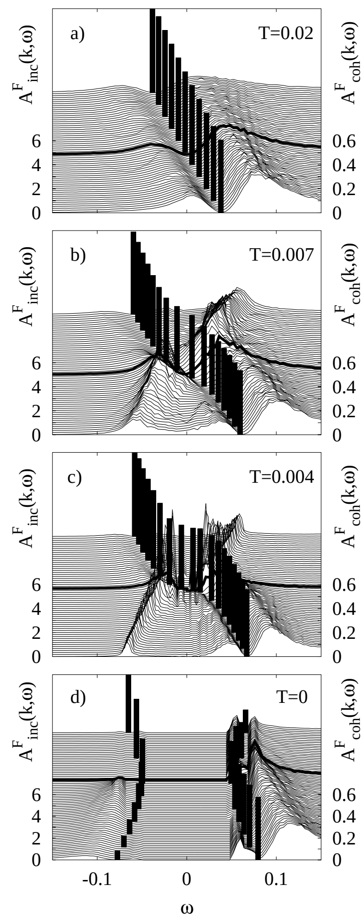

FIG. 1: *The single particle fermion spectral function $A^F(\mathbf{k},\omega)$ decomposed into its coherent component $A^F_{coh}(\mathbf{k},\omega)$ (thick bars whose height indicate the intensity of the delta like contributions) sitting on top of an incoherent component $A^F_{inc}(\mathbf{k},\omega)$ in the vicinity of $\mathbf{k_F}$ indicated by the bold spectral line) for the normal phase (a) above T^* ($T = 0.02$ D), (b) and (c)for the pseudogap region $T^* > T > T_c$ (0.007 D, 0.004 D) and (d) for the superconducting phase (in the ground state $T = 0$). The distance between the neighboring lines corresponds to changes in wavevector by multiples of $\Delta k = \pi/1000a$. Figure is reproduced from our paper [2].*

phase, slightly above T_c, such Bogoliubov shadow modes appear broadened and such behavior is in agreement with the experimental findings reported by A. Kanigel et al [1]. Upon further increasing the temperature those Bogoliubov shadow modes get overdamped and upon approaching T^* they fade away, due to life-time effects. A concomitant gradual closure of the pseudo-gap is then the signature of the phase uncorrelated pairing fluctuations.

The presence of a Bogoliubov spectrum above T_c together with other experimental facts, such as the residual diamagnetism (Ref. 25 cited in [1]) and the observation of vortices (Ref. 26 cited in [1]) bring further evidence that T_c must be related to a loss of long-range phase coherence. For the time-being, the experimental observation by A. Kanigel *et al* [1] works strongly in favor of the precursor scenario, which initially has been proposed by one of us [5, 8] and well before the experimental verification of the pseudogap phase by ARPES measurements.

We hope that in future, experimental groups would give some credit to such theoretical predictions, which might have stimulated such beautiful and important experiments and the physical insights.

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